Quantitative Analysis of Technology Futures: A conceptual framework for positioning FTA techniques in policy appraisal

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Abstract

Quantitative techniques for exploring future developments in Science and Technology (here called Future-oriented Technology Analysis (FTA)) are increasingly important in an era of big data and growing computational power. New quantitative techniques such as webometrics, altmetrics and prediction markets are complementing more traditional S&T indicators. While these techniques hold great promise, it is unclear how robust and appropriate is their use under different contexts. In order to help users think through their distinct values and limitations, in this article we discuss quantitative FTA techniques in the light of a general analytical framework. Following Stirling & Scoones (2009), we position FTA quantitative techniques according to their representation of (the incompleteness) of knowledge – i.e. the extent to which they portray their knowledge on probabilities and outcomes as problematic. This framework illuminates the implicit assumptions about the uncertainty, ambiguity and ignorance that distinct quantitative techniques make when exploring (in some cases "predicting") the future. We distinguish between techniques that tend to 'open up' awareness of new or unexpected futures, and others that tend to 'close down' by pointing out to likely futures.

Introduction

Since the middle of the last century, organisations and policy makers began to use a large number of techniques to investigate and influence the future. Several techniques have been proposed since the 1960s, some of which rely on quantitative methods – particularly many of the most recent ones based on the use of internet data (Eerola & Miles, 2011; Porter et al., 2004). In a recent NESTA report (Ciarli, Coad, & Rafols, 2012) we reviewed and classified 26 techniques employed in Future oriented Technology Analysis (FTA) grouped in 10 different families, and we discussed the contexts in which they are most widely used. Although we use here the terminology from the FTA tradition, we notice, *for the purposes of this conference, that FTA techniques are special case of S&T indicators and/or mapping that explore future developments*.

In this article we assess the FTA techniques reviewed by asking how practitioners represent knowledge when they use quantitative techniques for FTA. In other words, we study how the properties of different techniques allow the practitioner to "construct" different states of knowledge about the future.

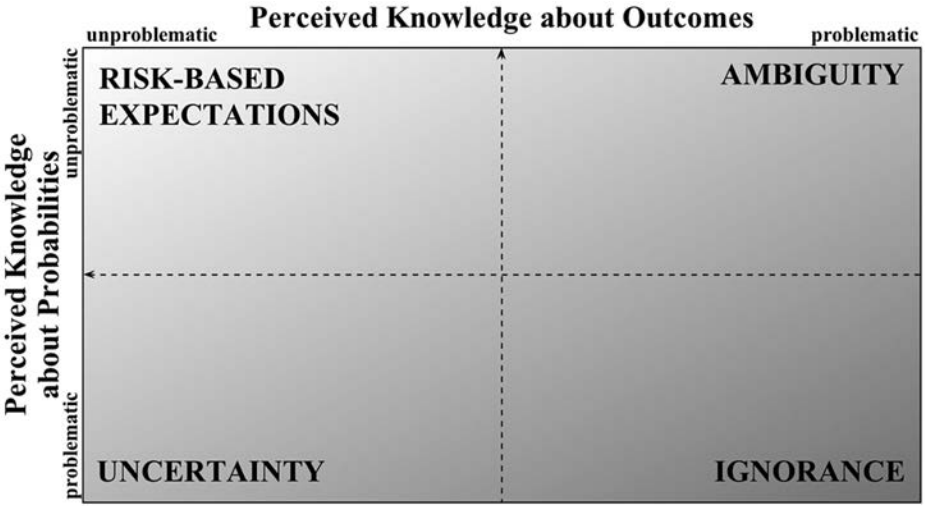
Following Stirling and Scoones (2009) we focus on two main dimensions: knowledge about outcomes and about probabilities. Under the first dimension knowledge is perceived as more or less problematic with respect to which outcome is more or less relevant when considering future states of the world. Under the second dimension knowledge is perceived as more or less problematic with respect to the probability that specific instances of an outcome will occur in the future. We take an explicit constructivist approach: the analyst using an FTA technique can only refer to a limited representation of the complexity of the world, and the outcomes of using a technique depend also on the perspective taken by the analyst and used to simplify the world.

We compare to which extent the use of different families of techniques tend to "open up" ("close down") the range of policy options (i.e. comparable outcomes) resulting from an FTA, and to which extent different techniques broaden (narrow) the range of inputs (i.e. sources of information) used in technology appraisal. We will answer questions such as: how does the use of specific FTA techniques represents knowledge and incertitude, in particular the very incomplete nature of knowledge regarding future technological outcomes? How do they change the way in which we represent knowledge on future events initially considered unknown?

Analytical framework: the incompleteness of knowledge

When an analyst decides to use a given FTA quantitative technique she makes a specific representation of knowledge, i.e. she assumes that some or all variables influencing aspects regarding the future technology can be known, others are uncertain, others are unknown and many others are irrelevant. Following Stirling and Scoones (2009), we distinguish two dimensions in the incompleteness of knowledge, as illustrated in Figure 1.

Figure 1. Representations of knowledge that users of different FTA quantitative techniques may make. Source: Stirling and Scoones (2009).



The horizontal axis describes the perceived knowledge about outcomes. On the left hand side of Figure 1 the analyst considers the outcome of the FTA analysis as not problematic, and assumes that it is fixed. For example, an FTA analysis in the 1950s or 60s might have assumed that urban means of transportation would be based on the combustion engine. Knowledge about the type of the dominant engine technology was perceived as not problematic. However, an analyst in the 2010s on urban means of transportation is likely to represent the possible type of technologies for urban transportation as relevant alternatives to evaluate. Not only there are diverse means (bicycles, cars, metro, tramways), but also she is likely to think that new technological means might appear or their research may be induced. Hence, the knowledge about the outcomes of technological innovation are represented as problematic, or unknown (right side of Figure 1), whereas in the 1960s they were often represented as not problematic, or known (left side of Figure 1).

The vertical axis describes the perceived knowledge about the likelihoods about a certain aspect of a technology, a plausible instance of one of the outcomes (the different technologies). If the analyst perceives that a certain instance can be calculated in a probabilistic manner with a known generation mechanism of the probability distribution and an expected probability of its occurrence, then she is assuming that the knowledge about likelihoods is not problematic. For example, one analyst in the 1960s may have assumed that combustion car ownership trends in a given city were sufficient to "predict" the number of automobiles in the years to come. One analyst in the 2010s might instead think that knowledge about the likelihood of combustion car ownerships is extremely problematic since it depends on a series of variables (public opinion on climate change, governmental regulations on pollution, public health measures, oil cost, and so on), which have behaved in an erratic way for the last 40 years.

This analytic framework leads to four potential "ideal manners of representing knowledge. It is in relation to these ideal representations of knowledge that we can now think on how different FTA techniques are conventionally perceived and used. We should emphasise that there is some flexibility in how an analysts use of a given FTA represents knowledge. Here we describe the conventional uses of the FTA techniques.

When neither knowledge about likelihoods nor knowledge about outcomes is represented as problematic, the analysts engage in *risk-based expectations* (top left of Figure 1). Here there is a "neat" focus on a given technology and a method to estimate one of its aspects. This would be the case of many simple quantitative FTA techniques, such as trend extrapolation. This is the type of approach which is often associated with scientific techniques, possibly because it allows quantification in a similar way that physics does. However, these methods are only valid to the extent that they ensure that exogenous conditions are controlled and fixed so that only the variables under investigation may have an effect on the outcomes. Yet, in practice, technology futures in the mid and longer terms unfold with many variables beyond control (public perceptions, energy source prices, other technologies, political and organisational preferences, events that cannot be known), changing radically and releasing unforeseen signals, having major effects on technological development.

Indeed, when dealing with future technologies, all sorts of changes in conditions – both endogenous and exogenous to the closed system analysed – assumed as stable may disturb the assumptions made by risk-based expectations FTA. If the analyst focuses on well-defined outcomes but represents the system as not being amenable to probabilistic analysis, then she moves into an area of *uncertainty* (bottom left in Figure 1). Roadmapping, which often includes quantitative description of technological trajectories, would be one such case. There is a consensus on the type of out-come desired, and hence the actors involved focus on achieving some given technological specifications. However, the roadmapping exercise is carried out without making assumptions on the likelihood of each instance of the outcome being achieved. A good example is the case of the International Technology Roadmap for Semiconductors (ITRS, http://www.itrs.net) which specifies expected outcomes, while acknowledging uncertainty without carrying out probabilistic assumptions.

Another way of representing the state of knowledge is to assume that probabilities are not problematic, but that the knowledge of outcomes is problematic, because of conflicting assessments on the desirability of these outcomes. Such state is characterised by *ambiguity*. In principle, one cannot find many examples of quantitative FTA techniques leading to ambiguity because in quantitative approaches incomplete knowledge of type of outcomes often occurs with incomplete knowledge on likelihoods. However, many approaches using risk-based expectation type of assessment over diverse potential outcomes could fall into ambiguity. This would be the case, for example, of an exercise looking into future of urban transportation where the stakeholders agreed on the likelihood that various technologies (bicycles, cars, metro, etcetera) were used in a near future on the basis of trend extrapolation, but the stakeholders did not agree on the desirability of those.

Finally, the state of knowledge can be represented as *ignorance*. This is the state of knowledge that Donald Rumsfeld, then US Defence Secretary, made famous with his quote on "unknown unknowns", namely those "things we do not know we don't know." In short, when an analyst considers that she is in a state of ignorance, she assumes that she does not know what are the potential types of outcomes (or their desirability), nor the probability that they occur. One might think that ignorance is the most sensible way to represent technological futures, given that futurology or forecasting have an extremely bad record on prediction. But ignorance is a difficult state to work with. One can try to carry out forecasting or foresight with some known potential outcomes, but how should one characterise quantitatively unknowns?

The representation of knowledge by users of FTA techniques

In Figure 2 we map the 10 groups of FTA quantitative techniques surveyed in Ciarli, Coad and Rafols (2012) according to their relative position with respect to the representation of knowledge that a user has before an FTA exercise. For all techniques the knowledge on probabilities is initially represented as problematic.

Techniques vary to a large extent with respect to how the knowledge on outcomes is represented. Some techniques are prevalently employed when the outcomes of the technology under investigation are already perceived as relatively certain. For example, the use of Trend Analyses to describe the diffusion of a technology in terms of the share of users. Other techniques are employed when the knowledge about outcomes is presented as highly problematic. In this short version of the article, we only illustrate how the use of FTA changes the representation of knowledge with reference to Trends Analyses (Figure 3) and different types of Modelling (Figure 4). Figure 5 presents all the techniques reviewed.

The choice of techniques that are part of the Trend Analyses family tends to have a closing-down effect since the beginning of an FTA exercise because of the use of very restrictive assumptions. Their use tends to increase the certainty about the representation of knowledge even more.

In the case of modelling, the effect depends on the type of modelling. Different economic methods have very different effects on technology appraisal (Figure 4). On the one hand Prediction Markets close down on one single outcome and a well defined expected value with low variance (Risk-Based Expectations). On the other hand, Input-Output models may even open up to different scenarios, although the relevant outcomes are usually defined at the outset. Simulation Models usually allow to open to a number of different, even non-predicted outcomes. Starting from a condition of ignorance – fewer assumptions on the outcomes, Quantitative Scenarios represent one relatively elaborate way to use Simulation Modelling. Their aim is to find conditions under which a large number of different outcomes can be realised. The only reduction in policy space occurs towards a perceived increase of knowledge about the likelihood of the different outcomes. This is achieved thanks to the combination of a large number of conditions defined by a number of parameters.

Figure 2. The representation of knowledge about outcomes and probabilities before an FTA.

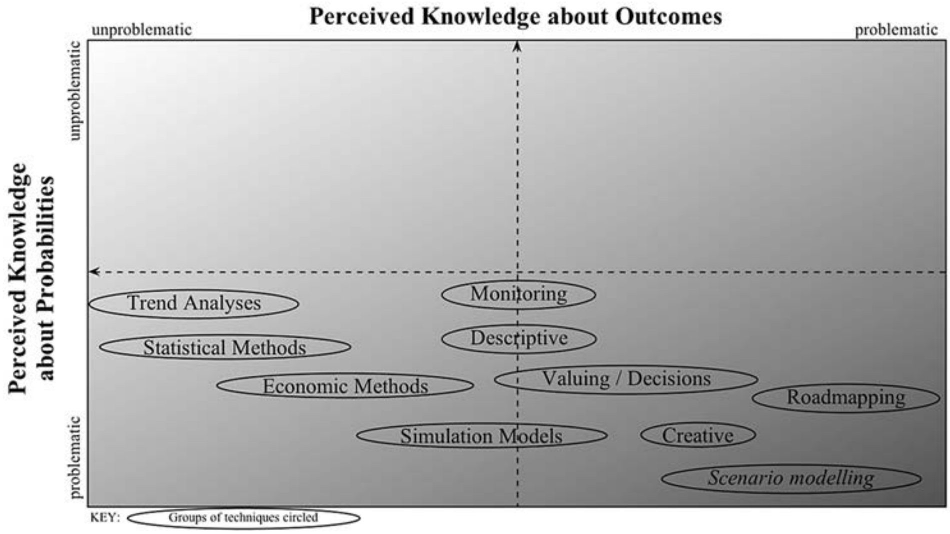


Figure 3. The change in the representation of knowledge about outcomes and probabilities using an FTA quantitative techniques. The case of Trend Analyses.

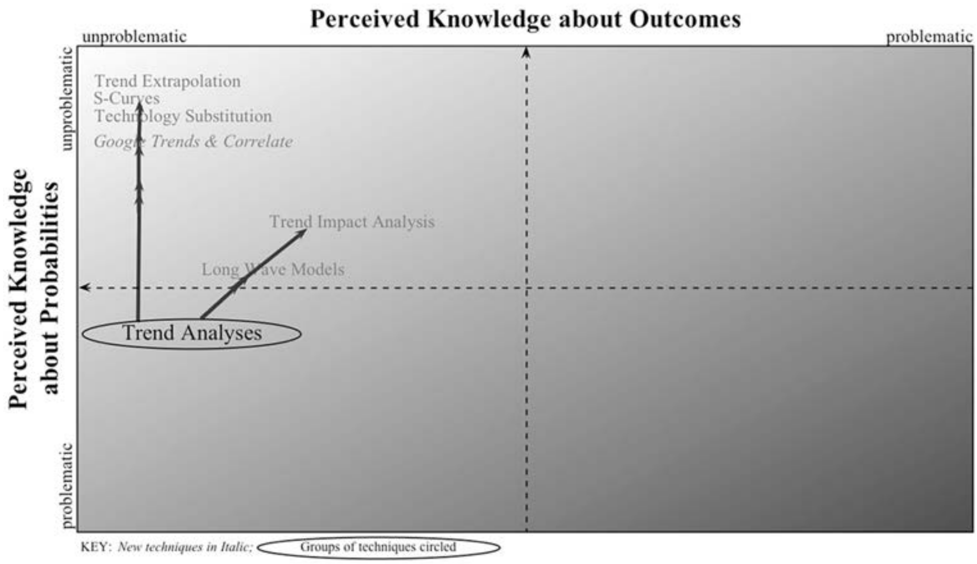


Figure 4. The change in the representation of knowledge about outcomes and probabilities using an FTA quantitative techniques. The case of different types of modelling: Economic Methods, Simulation Models and Scenario Modelling.

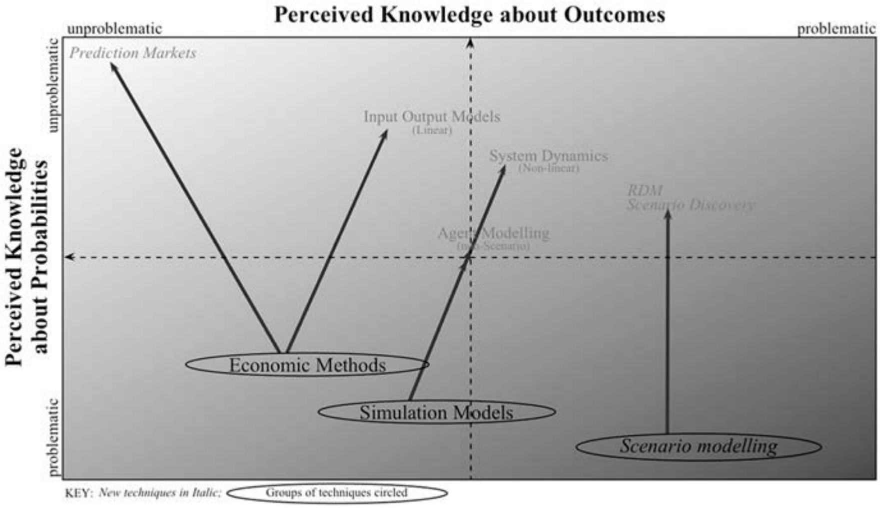
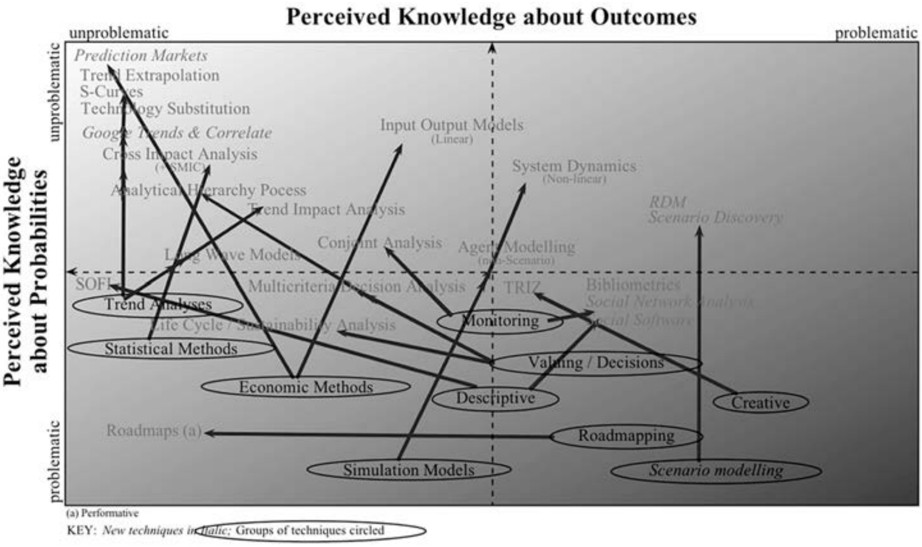


Figure 5. The change in the representation of knowledge about outcomes and probabilities: using techniques.

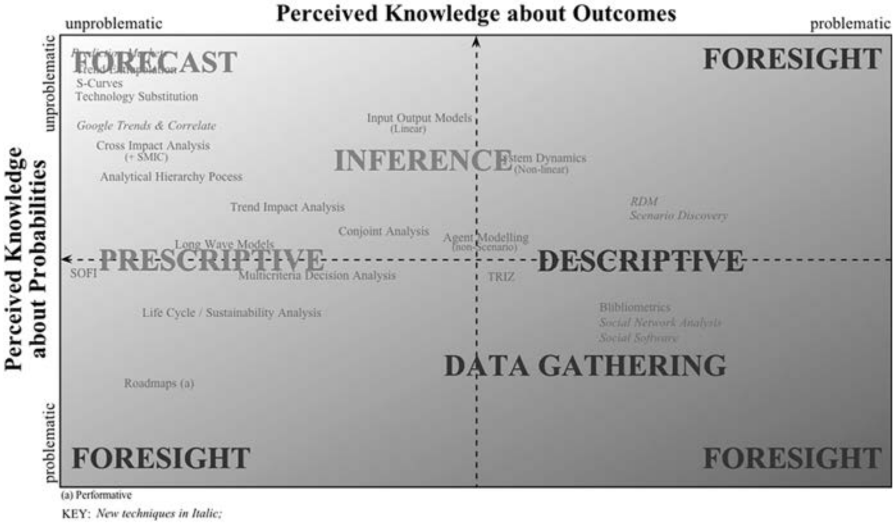


Distinguishing between foresight and forecasting

FTA techniques that focus on a given outcome and specific properties in order to provide allegedly quantitatively rigorous approaches (generally falling in the risk-based expectations zone, Figure 6, top left), do so at the expense of putting blinders to phenomena which are very difficult to quantify and which may dramatically alter the results of the "prediction" (an unexpected war, conflict, or terrorist attack). These are the type of approaches that resemble in one way or the other the traditional forecasting literature.

As a result of the repeated failure of forecasting exercises, policy-oriented analysis of future technologies puts the emphasis on foresight rather than quantitative forecasting. This practical focus acknowledges that the usefulness of foresight lies in opening up a process to discuss technological futures in the face of insurmountable incertitude, rather than trying to predict the future. The contribution of quantitative techniques to foresight seems to be best achieved via FTA techniques that represent knowledge as incomplete, either in terms of the probability of known outcomes or in the type of outcomes.

Figure 6. The representation of knowledge about outcomes and probabilities and their role in Forecast and Foresight FTA.

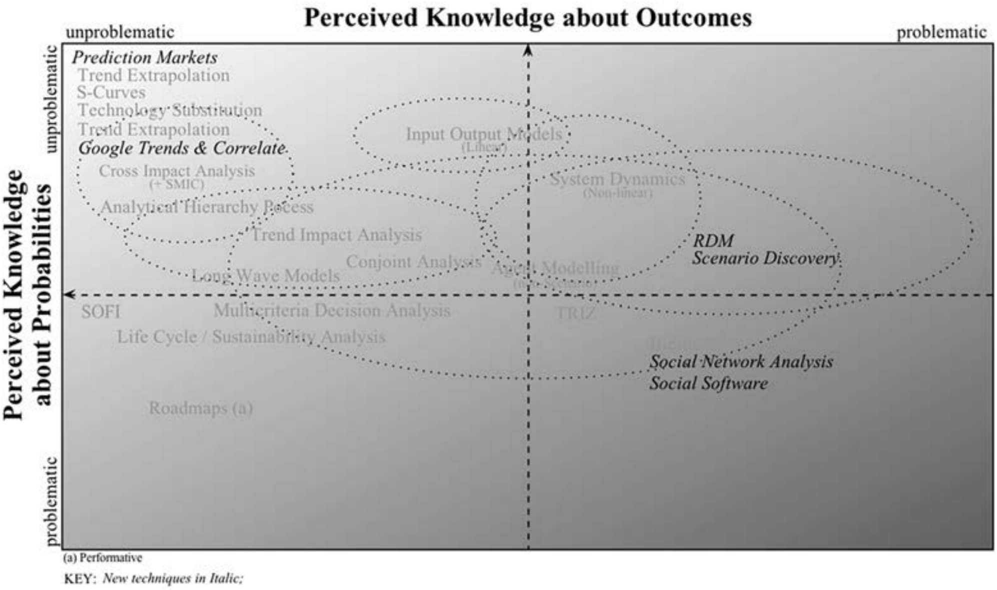


Breadth of inputs and "participation" in FTA: the role of new techniques

The advantage in using new crowd-sourcing based techniques is that they collect information from a very large number of users, rather than from a small number of experts or from structured sources that acquired an authoritative status such as patent and scientific publication datasets. In other words, they broaden the source of inputs, including outputs and opinions that were not usually included in FTA. Indeed, by monitoring the opinions and sentiments on blogs and social network such as Twitter, it is possible to use more or less spontaneous opinions about past, present and future events (the degree of spontaneity is increasingly problematic: monitoring is already resulting in manipulations).

Although these methods collect very diverse types of information and therefore they broaden up the diversity of information sources, they do not necessarily have an opening up effect in decision making. Let us think for example in carbon-based nanotechnologies. The exponential boom in presence of fullerenes and carbon-nanotubes in databases and the web in the 1990s meant that most quantitative FTA techniques would have focused on the impact of these two types of carbon materials. This focussing (closing-down) effect might have had a blinding effect, preventing to see that there was ongoing research on other carbon-based nanomaterials, and hence it would have missed out the possibility that graphene, another carbon-based nanomaterial, would become important. Instead a simple qualitative study that discussed diverse carbon-based nanomaterials could have mentioned graphene, since it had been studied theoretically for decades. This example illustrates that quantitative power does not imply capacity for seeing more alternative futures – an opening up of perspectives.

Figure 13. New techniques for FTA.



Discussion

The improvements in computational capabilities are resulting in the creation of new FTA techniques that promise great improvements in their capacity to generate reliable predictions. The analytical framework we proposed should help discern the type of contribution to policy that they can make.

Our analysis suggests that the most promising quantitative methods for conducting FTA in a sophisticated manner are those that allow the analysis to explore states of ignorance – in which neither future technology outcomes nor their probability are known – and bring the user to a state of ambiguity, in which future outcomes are compared against different probabilities of occurring, and users can evaluate a number of trade-off.

These exercises are not capable to predict instances of outcomes, but they help explore the future in a conditional manner, acknowledging the incompleteness of knowledge. Using the techniques plotted in the ambiguity quadrant of the knowledge map, one can investigate the possibility of reaching certain outcomes under circumstances that are unknown but can be investigated in a conditional manner. We suggest that these types of agent modelling and scenario modelling are the ones which can make a more positive contribution to policy-oriented FTA – by avoiding narrow prediction and allowing plural exploration of future technologies.

Finally, monitoring methods (such raw bibliometrics or web-scraping) may be able to identify potential outcomes and be useful for activities such as horizon-scanning, but they have limited analytical potential on their own. Therefore, their usefulness depends on their implementation within a larger foresight methodology.

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